Comparisons of Polar satellite observations of solitary wave velocities in the plasma sheet boundary and the high altitude cusp to those in the auroral zone

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ABSTRACT: Characteristics of solitary waves observed by the Polar electric field instrument magnetosphere in the high altitude cusp, polar cap and plasma sheet boundary are reported and compared to observations of such waves in the auroral zone. Initial studies presented herein show that, at high altitudes, the solitary waves are positive potential structures (electron holes), with scale sizes of the order of 10's of Debye lengths, which usually propagate with velocities of a few thousand km/s. At the plasma sheet boundary, the direction of propagation can be either upward or downward; whereas at the leading edge of high altitude cusp energetic particle injections, it is downward. For these high altitude events, explanations based on ion modes and on electron modes are examined. The electron mode interpretation is shown to be more consistent with observations. Previous studies have shown that, in the auroral zone, solitary waves with negative potential pulses, which are usually observed in upflowing ion beam regions, propagate upward at ~a few hundred km/s. An explanation based on previous analytic studies and simulations of ion acoustic solitary waves is consistent with the velocities of the low altitude, negative potential structures.

I. Introduction

In the earth's magnetosphere, there are many regions where narrow boundaries and large gradients in particle properties and/or fields occur. Such regions often contain currents flowing along the earth's dipole magnetic field as well as other sources of free energy such as ion and/or electron beams. Nonlinear electric field structures are often observed at these boundaries, motivating the inclusion of a waveform sampling ('burst') mode in the Polar electric field instrument to provide the first simultaneous measurements of the full 3d electric field and magnetic field at sample rates up to 8000 samples/s. One type of nonlinear structure which has received much study is solitary waves which are the subject of this paper.

Solitary waves, which were interpreted as negative potential pulses traveling up the magnetic field, were first observed in the auroral zone [Temerin et al., 1982, Bostrom et al., 1988]. Later, lower amplitude solitary structures, interpreted as electron holes, were identified in the distant plasma sheet [Matsumoto et al., 1994]. Estimates of the velocity of solitary waves in the auroral zone have been provided by several research teams, using both electric field and Langmuir probe instruments on different satellites. The solitary waves have been associated with the ion acoustic mode and have been identified as ion holes. The first observations, made by the S3-3 satellite electric field instrument, indicated that the waves must be traveling faster than ~50 km/s [Temerin et al., 1982]. Viking satellite Langmuir probe observations [Bostrom et al, 1988] indicated that the speed was slower (~5-50 km/s). Recent Polar observations [Mozer et al., 1997; Bounds et al., 1998] have shown that the propagation speed is usually 100's of km/s. McFadden [1998] have provided a possible explanation for the discrepancy between the Viking observations and those from S3-3 and Polar based on the operation of Langmuir probes in a low density plasma. In addition, utilizing data from the FAST spacecraft, Ergun et al. [1998] have identified a new type of solitary wave, associated with cold electron beams, which propagates upward at ~4500 km/s. These waves have an electromagnetic signature and are interpreted as electron holes traveling with the beam. Similar structures in the low altitude Polar data were described by Mozer et al. [1997]. Preliminary results from Polar have also provided evidence for fast moving solitary waves at high altitudes [Cattell et al., 1998; Franz et al, 1998].

In this letter, data from the Polar EFI burst mode are used to determine the propagation speeds of solitary waves observed in the plasma sheet boundary (~4-7 R_e) and the high altitude cusp (~5-9 R_e). We compare the observed solitary wave characteristics to plasma properties in order to address the similarities and differences between the solitary waves observed in these regions, as well as the solitary waves previously identified in low altitude auroral zone data. In Section II, the data sets and methodology are described. Solitary wave examples from both regions are presented in Section III. The significance of the propagation speed differences will be discussed in Section IV, using theoretical models of both ion acoustic and electron acoustic solitary waves and simulations of ion acoustic solitary waves.

II. Data sets and methodology

The data for this study were obtained as the Polar satellite traveled through the cusp and polar cap at radial distances of ~5 - 9 R_e, and traversed the plasma sheet boundary at ~4-7 R_e. Electric and magnetic field data from DC to ~8000 Hz were utilized. The spacecraft potential, which is indicative of thermal electron density [see Mozer et al., 1993; and Pedersen, 1995], was used to provide the initial identification of the plasma sheet boundary and regions of cusp particle injections. Ion composition measurements, made by the TIMAS instrument [Shelley et al., 1995], were examined to determine the probable source region and plasma characteristics. Hydra instrument observations [Scudder et al., 1995] provided additional information on the particle distributions and moments in these regions.

The electric field and spacecraft potential were measured by the double probe electric field instrument on the Polar satellite [Harvey et al., 1995] which acquired bursts of high time resolution data at rates of 1600 to 8000 samples per second for periods of ~2-~30 seconds. Electric field data were rotated into a magnetic field-aligned coordinate system and the parallel component was examined for candidate solitary waves. Timing analysis was limited to events where one of the two spin plane boom pairs is nearly aligned along the magnetic field. In these cases, the signal from each single probe was splined to provide an identical time basis for all signals and spacecraft potential variations were removed using the data from the perpendicular boom pair. As shown schematically in Figure 1, the time delay between the observation of the solitary wave signal measured by opposing probes was determined using a cross correlation analysis. Coupled with the projected probe separation along the magnetic field, the time delay was used to estimate the propagation velocity of the solitary waves. Details of this procedure will be described elsewhere [Dombeck et al., manuscript in preparation]. The AC magnetic field from the search coils [Gurnett et al., 1995] were sampled in the burst memory at the same rate as the electric field. DC magnetic field data, obtained from the fluxgate magnetometers [Russell et al., 1995], were utilized to determine the association of the solitary waves with field-aligned currents.

III. Examples of solitary wave observations

An overview of a plasma sheet boundary crossing at ~6.3 Re and at ~01:30 MLT on March 28, 1997 is shown in Figure 2. The transition from lobe to the plasma sheet is indicated by the increase in the negative of the spacecraft potential (panel a), corresponding to the increase in electron flux (panel b). The plasma sheet boundary, indicated by the variable values of the spacecraft potential and the electron flux (intermediate between lobe and plasma sheet values), contained several field-aligned current sheets indicated by changes in the eastward component of the magnetic field (panel c). The waveform burst occurred at a transition between downward and upward current, in a region containing low energy oxygen and hydrogen conics, and low energy electrons peaked in the upflowing direction. A 50ms sample of the electric field parallel to the geomagnetic field (panel d) indicates that the solitary wave field is first negative (upward, away from the earth) and then positive (downward, towards the earth) with amplitudes up to >50 mV/m. Since the measured time delays correspond to upward velocities (of ~1000 – 2500 km/s), the solitary waves are positive potential structures (i.e. ion enhancements or electron holes) with parallel scale sizes of ~2-8 km. In addition, there are often unipolar perpendicular fields, indicating that the solitary waves are not one-dimensional. There were no signatures of the solitary waves observable in the AC magnetic field. Using Hydra estimates of density and temperature , the Debye length , λ_D, is ~0.25 km, and the ion sound speed, c_s, is ~100 km/s. There is, however, evidence of an energetic ion population, suggesting that c_s is probably closer to 500 km/s .

In contrast to the 3/28 event, the solitary waves observed during the burst event on March 10, 1997, shown in Figure 3, occurred in a region of downward current (panel c), well inside the plasma sheet. At this time, there was a few keV upflowing ion beam (see panel bb which shows the ions with pitch angles between 150° and 180°). The observed solitary wave electric field signatures (see examples shown in panel d) had the opposite polarity (first downward, then upward) from the previous example. However, since the measured time delays correspond to a downward velocity, the structures were again positive potential pulses. In this case, the Hydra moments correspond to c_s ~400 km/s. The observed velocities in both plasma sheet cases were ~2-5 times the ion sound speed. It should be noted that for some structures, no delay was observed which suggests that for some solitary waves the propagation speeds were even higher (>2500 km/s). The observed scale sizes were ~2-30 λ_D.

An example of data obtained at an encounter with a cusp energetic particle injection on 4/24/98 at a radial distance of ~6 Re and at ~11:30 MLT is presented in Figure 4. The cusp injection which occurred at ~17:12 UT can be seen in the spacecraft potential (panel a). This identification was confirmed by examination of the TIMAS data which showed an intense velocity dispersed injection of H^+ (panel b) and He^{++} (panel c). The perturbation in the eastward component of the DC magnetic field (not shown) was indicative of a current into the ionosphere. An ~6s burst began at 17:40:20 UT, and the component of the burst electric field which is parallel to the magnetic field is shown in panel d. Packets in the parallel component with magnitudes of 10-20 mV/m are groups of solitary waves. The quasi-periodic nature of the solitary wave bursts and other aspects of the waves are discussed elsewhere [Cattell et al., 1998b]. Herein, we focus on the solitary wave structure and propagation. The measured time delays correspond to propagation towards the earth (i.e in the direction of the injected ions) at speeds of ~1000-2000 km/s. Individual solitary waves initially have a positive (downward) electric field, followed by a negative (upward) field. For the observed downward propagation, this is consistent with a positive potential solitary wave, as was also observed in the plasma sheet boundary events. Although plasma measurements from Hydra were not available at the time of the burst, electron density and temperature for this interval, estimated from the spacecraft potential and Hydra observations in similar cusp injections, resulted in λ_D ~0.01- 0.03 km, and c_s ~40 km/s. The observed solitary wave durations yield parallel scale sizes of ~0.5-1 km, or ~15-100 λ_D. Several other cases of solitary waves during cusp injections have been examined and the solitary waves have comparable structure and velocities. In addition, the characteristics of solitary waves during several high altitude cusp/polar cap crossings which were not associated with injections have been determined. In contrast to the injection events, the wave velocity in these cases was usually upward. Statistical studies are underway to verify this correlation.

IV. Discussion and conclusions

We have presented examples of waveform data obtained in the high altitude cusp and at crossings of the plasma sheet boundary. Large amplitude solitary waves are commonly observed, as are wave packets of the type described by Cattell et al. [1998a] and Mozer et al. [1997]. Fourier transforms of the regions with solitary waves result in very broadband spectra, suggesting that much of the previously reported broadband electrostatic noise in all these regions is due to these nonlinear waves. The high altitude solitary waves have high propagation speeds of ~1-2 x 10^3 km/s, and are positive potential structures (i.e. electron holes or ion enhancements). This is very different from the type of solitary waves first observed in the auroral zone at low altitudes [Temerin et al., 1982, Bostrom et al., 1988] which are negative potential structures (identified as ion holes) travelling at 100's of km/s [Mozer et al., 1997; Bounds et al., 1998]. The structures described herein are more similar to the recently identified 'fast solitary waves' in the low altitude auroral zone [Mozer et al., 1997; Ergun et al., 1998; Bounds et al., 1998] which have been classified as electron holes traveling at velocities up to ~5000 km/s. The lack of an AC magnetic signature in association with the solitary waves described herin is not inconsistent with this possibility since the expected amplitudes are generally below the instrument noise level.

Ion acoustic solitary waves have been extensively studied theoretically [Lotko and Kennel, 1983; Hudson et al., 1983; Marchenko and Hudson, 1995; and references therein]. Simulations with both a cold background and an ion beam have shown that the solitary waves develop as ion holes in the cold, background plasma when the ion beam is weak. The expected propagation speed, V_{sw}, is given by $V_{sw}=V_b$ +/- c_s in the frame of the background plasma, where V_b is the beam speed, consistent with analytic studies [Lotko and Kennel, 1983]. In the case of the simulation which included a cold, ionospheric background, this resulted in speeds of 10's of km/s. However, data from the FAST satellite are consistent with no cold plasma in ion beam regions [Strangeway et al., 1998]. Hudson [1997] suggested that, in the absence of a cold background in ion beam regions, the oxygen beam would act as the cold background plasma, and the hydrogen beam as the beam. Hot plasma sheet electrons are the third component and determine the sound speed. Using these particle populations and an ~ 1 keV beam, the solitary waves would propagate in the satellite frame at ~few hundred km/s upward. This is consistent with the low altitude auroral zone observations of negative potential (ion hole) structures.

To ascertain whether the observed characteristics of the high altitude solitary waves are consistent with an ion mode, we extend this argument to the high altitude regions to determine if a plausible explanation for the observed propagation speeds can be made. In cusp injections, H^+ and He^{++} downflowing ions and cool magnetosheath electrons are the main particle populations. The He^{++} ions could act as the background population for the growth of ion holes. The sound speed is low, ~40 km/s, while the injected ion speed is ~500 km/s. The observed solitary waves are positive potential structures which are propagating downward. This is consistent with the conclusion of Lotko and Kennel [1983] that compressive (i.e. positive potential) ion acoustic solitons can grow when $V_b > \sim 10\ c_s$, and with the simulations results [Marchenko and Hudson, 1995] which showed the compressive mode growing for strong beams (beam density comparable to background ion density). The structures propagate in the direction of the ion beam at approximately twice the sound speed in the background frame. For the observed parameters, the predicted speeds are ~600 km/s which is comparable to, but somewhat less than, the observed speeds.

At the high altitude plasma sheet crossings, the hot, plasma sheet ion population may act as the background plasma. The sound speed is very large, ~500 km/s. If the positive potential mode could grow, its propagation speed would be $\sim 1 \times 10^3$ km/s, comparable to the observed velocities of $\sim 1\text{-}2 \times 10^3$ km/s. However, the Lotko and Kennel [1983] study predicts that positive potential modes could not grow for the observed plasma parameters. The Marchenko and Hudson simulations suggest a very dense ion beam would be needed, and such beams are not always observed. In the 3/28 event, there was no ion beam. Although a dense beam was observed in the 3/10 event, it was an upward beam which should result is upward propagation for ion mode solitary waves. The observed waves , however, were travelling downward.

The above discussion has described several difficulties with an ion mode explanation for the high altitude solitary waves, including the high speeds, direction of propagation in some cases, and the fact that the solitary waves are positive potential structures. An additional problem is that simulations [Barnes et al., 1985] have suggested that the growth of ion solitary waves requires that the plasma be strongly magnetized (f_{ce}/ f_{pe} >>1) which is not the case for the observed high altitude events. For the plasma sheet boundary crossings, f_{ce}/ f_{pe}=~2; for the cusp case, f_{ce}/ f_{pe}<1. It is likely, therefore, that these solitary waves are an electron mode, either an electron hole or an electron acoustic solitary wave, rather than an ion mode. Both electron acoustic solitons [Dubouloz et al., 1991; Mace et al., 1991] and electron holes [Ergun et al, 1998] move at higher velocities, greater than the electron acoustic speed, and the electron beam speed, respectively, comparable to those observed. Electron acoustic solitary waves can be positive potential structures and electron holes always are; neither require that the plasma be strongly magnetized. Further studies of the solitary waves and associated plasma distributions, as well as more detailed theoretical studies, are needed to identify definitively the mode of the high altitude solitary waves, to determine whether all high altitude solitary structures have the same explanation, and to determine whether the mechanisms are the same as for the low altitude electron holes or are like the solitary waves observed in the distant plasma sheet [Matsumoto et al., 1994].

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FIGURE CAPTIONS

Figure 1. A schematic drawing illustrating how the propagation velocity is determined. The four spin plane probe are shown. In this case, probes 3 and 4 are nearly aligned with the geomagnetic field. The effective boom length, L_B, is 50m * cos(θ). All voltages are splined to a common time base, then the time delay, t_{DELAY}, between V_+ and V_- is determined by cross-correlation analysis. The central voltage, which provides the reference voltage for the probes, is calculated using the mean of the perpendicular probes (in this case, V_1 and V_2) to remove effects due to the response of the spacecraft.

Figure 2. Plasma sheet boundary crossing on 3/28/97: (a) Negative of spacecraft potential; (b) Electron flux (over all angles); (c) Eastward magnetic field perturbation; and (d) 0.5 ms snapshot of electric field parallel to the geomagnetic field.

Figure 3. Same as Fig. 2 for 3/10/97 with the addition of panel (bb) Ion flux at pitch angles of 150-180°.

Figure 4. High altitude cusp crossing on 4/24/97: (a) Negative of spacecraft potential; (b) H^+ flux; (c) He^{++} flux; and (d) Electric field parallel to the geomagnetic field for burst.